Human Factors Aspects of Power System Voltage Visualizations

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Abstract

This paper presents experimental results associated with the human factors aspects of using color contours to visualize electric power system bus voltage magnitude information. Participants were divided into three groups: the first group only one-line numeric data, the second only one-line contour data, while the third saw both. The purpose of the experiment was to determine how quickly participants could both acknowledge low voltage violations and perform corrective control actions. Results indicated the contour only visualization resulted in the quickest voltage violation acknowledgements, while the numeric data only visualization resulted in the quickest solution times. Testing was done using a modified version of the IEEE 118 bus system.

1. Introduction

One area in need of new research is the visualization of electric power system operation and analysis information. Traditionally, the information associated with power systems has been represented either as numerical fields on one-line diagrams, or by tabular list displays. Additionally, in a utility control center an overview of the system is usually available on a static map board with the only dynamic data shown using different colored lights. While these approaches may have adequately met the needs of a vertically integrated utility, with restructuring they are increasingly inadequate. This paper presents results of human factors experiments on the use of color contours to represent power system voltage magnitudes [1].

The use of color contouring in one-line diagrams attempts to capitalize on the well-known benefits of color-coding in the human factors literature. For example, color can be used as a highlighting feature that attracts attention to a particular area within a display, thus reducing the size of the search space [2] and facilitating target detection [3]. Furthermore, the mental stage at which color codes are interpreted generally occurs early during perceptual processing whereas the interpretation of numeric codes generally occurs at a much later and more effortful cognitive level of processing [4]. Therefore, the speed in which color codes can be interpreted and compared is often faster than numeric processing. Thus, color contouring in one-line diagrams may facilitate the detection and comparison of voltage violations in large power systems compared to traditional numeric coding.

Still, there may be certain costs and limitations to the use of color contours. For example, the number of colors that can be optimally used in a display are bound by the human limits of absolute judgment. In using color contours, an operator needs to differentiate between colors to understand what voltage value a color represents. Absolute judgment experiments have typically shown that errors begin to be made in discrimination tasks when five or six different stimuli exist. For example, [5] found that this guideline applied specifically to color as well when colors represented a value or meaning. Therefore, to avoid incurring costs only five or six colors should be used to represent colors that must be categorized. A further cost associated with color is that no natural continuum exists. There is no inherent meaning that guides people to judge one color being greater or less in value along some dimension [4]. Finally, the issue of clutter is often involved with the use of color. Color, if not used carefully, can unintentionally conceal or hide important aspects of a display. This occurs by overlapping, blending, and inundating the display with multiple colors. Contours in one-line diagrams can often be of different sizes and invoke a number of different colors, which may inadvertently cover up numeric bus voltage fields or other one-line elements.

In a previous study by the authors the benefits of color contouring within a one-line diagram were examined using a 30 bus power system [6]. In that study, color contouring was shown to have an effect on the type of strategy that operators' adopted for acknowledging voltage violations. Specifically, operators using a one-line display with contouring generally acknowledged the bus with the worst violation (corresponding in that study to the largest color contour) more often than the equivalent buses when the information was presented either with a tabular display or as numeric fields on a one-line diagram display without contours. Thus, the contours did prove

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beneficial for attracting attention to the bus with the worst violation. Still, whether such benefits occur when larger and more realistic power grids are employed needs to be determined. Indeed, with an increase in grid size comes an increase in the potential cost associated with contouring, such as the possibility of exceeding the human operator's ability to process and compare multiple contour colors, as well the potential for increase clutter produced by multiple contour locations.

The purpose of the present paper is to address these issues by examining the ability of operators to detect and solve voltage violations on a modified version of the IEEE 118 bus system. Voltage information was presented to the participants using either a one-line diagram with contours, a one-line diagram with numbers, or a one-line diagram that combined both contours and numbers. The detection task required participants to first locate and acknowledge the bus experiencing the worst voltage violation. The solution task then required them to close one or more capacitors to correct all the low voltage violations. The amount of time and level of accuracy for both the detection and solving task were recorded and compared across display groups.

2. Experimental Setup

For the experiment 43 participants (38 men and 5 women) were recruited from electric power systems classes at the University of Illinois, Urbana-Champaign. All participants were required to have either completed, or be currently enrolled in, at least one class in the electric power systems area. The average number of power systems classes taken either currently or in the past by the participants was 1.56 (SD =0.91), with a range from 1 to 4. The mean age of participants was 21.28 years (median age was 21.00 years), with a range from age 19 to age 29. Participants were paid $12.00 an hour for their voluntary participation.

The experiment itself was run using a modified version of the PowerWorld® Simulator software. This package uses a full ac power flow model of the system. The software was run on a Dell Optiflex 800-Mhz computer with 128 megs of RAM and a 20-inch Trinitron monitor. A mouse was used to input and progress through the experiment. The main user interaction with the system was via a one-line diagram of the 118-bus power system network; a generic view of this one-line is shown in Figure 1.

During the course of the experiment the 118 bus system was subjected to a variety of different contingencies, each causing low bus voltage magnitudes, defined here as being below 0.96 per unit, at one or more system buses. The contingencies consisted of line and/or generator outages. The number of voltage violations per trial ranged from one to thirteen. Following each contingency the presence of voltage violations was indicated both audibly by having the computer beep and visually using one of the three display conditions discussed in Section 3. The participants were then required to perform two consecutive tasks. First, they had to acknowledge the bus with the worst voltage violations (i.e. the one with the lowest per unit voltage), indicating that they had identified the particular location of the worst voltage violation. The voltage violation was acknowledged by clicking directly on (or near) the bus symbol itself. Upon the acknowledgement of the correct bus, the audible alarm was terminated and the second task began. The second task was to do corrective control actions to restore the voltages to acceptable values. The voltages were corrected by switching in one or more capacitors to either their open or closed positions.

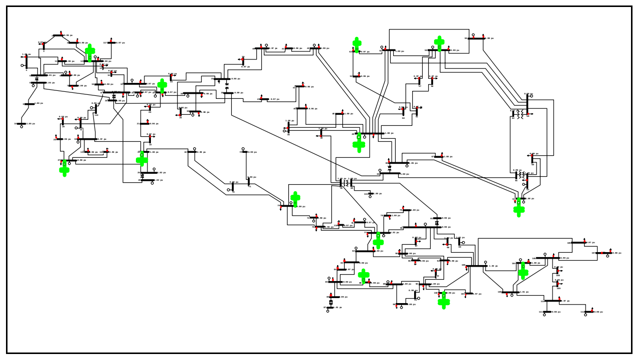

Figure 1: 118 Bus One-line with Capacitors Highlighted

3. Display Conditions

Participants in the study completed the experimental task using one of three display conditions, all of which were derived from the one-line diagram shown in Figure 1. The different display conditions were 1) number-only: a one-line diagram with numbers (per unit voltage values), 2) contour-only: a one-line diagram with color contours, and 3) number-plus-contour: a one-line diagram with both numbers and color contours.

3.1 Number-Only

In the number-only group the Figure 1 one-line was augmented to include numeric bus voltage magnitude fields for each of the 118 buses. The bus voltage values were listed as black numbers beside the associated buses and their voltage values changed dynamically as the system status changed. Initially all the voltages were within their limits (i.e., above 0.96 per unit). Following the contingency one or more of the voltages would be below the voltage limit. Voltage values that are below their limit were shown using a larger bolded red font (changing from 2mm to 4mm) on the one-line, with Figure 2 providing an example. Following the contingency the participants were firstly requested to acknowledge the bus that has the worst (lowest) per unit voltage by clicking on the bus symbol itself or on the red voltage value on the one-line. Once the worst voltage violation was acknowledged the beeping would stop.

Once the beeping stopped, the participants were asked to correct the voltage problems by switching in one or more capacitors, which was performed by clicking on the capacitor symbols. When a capacitor was open its small circuit breaker symbol (shown near the top of the capacitor) was an unfilled green rectangle. When the capacitor was closed the circuit breaker changed to a red filled rectangle. Participants were not able to perform capacitor switching until the worst voltage violation had been acknowledged. As the participants switched the capacitors the one-line display was updated with the new voltage values. When all the voltage problems were fixed, a screen indicating that the scenario is complete would be displayed and the next scenario would begin.

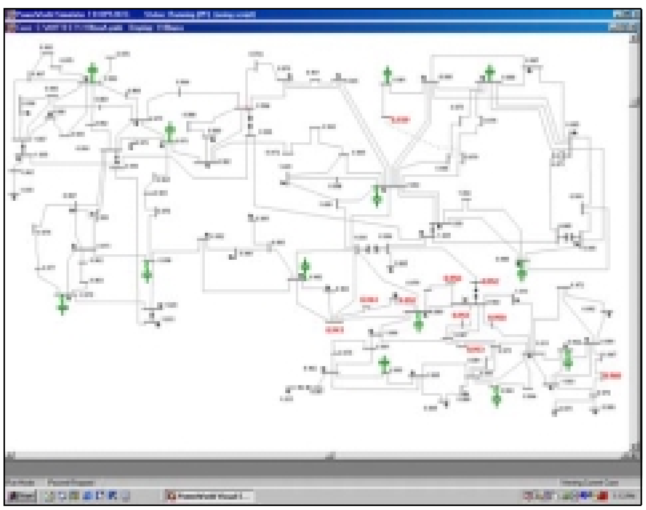

Figure 2: Number-only One-line

3.2 Contour-Only

In the contour-only group the Figure 1 one-line was augmented to include a color contour of the voltage values; no numeric voltage fields were shown. The contour color mapping used was such that as long as there were no voltage violations there was no contour. But when a voltage limit violation occurred, the region surrounding the bus experiencing the low voltage became shaded using a contour pattern that ranged from green to yellow to orange to red to dark red, with the dark red indicating the lowest voltage. The size and the color of the contour were depicted according to the severity of the voltage and its impact on nearby buses. The color key for the meaning of the color and contours was shown on the bottom left-hand side of the display. No contours were shown for buses with acceptable voltages. Figure 3 shows an example of this display condition.

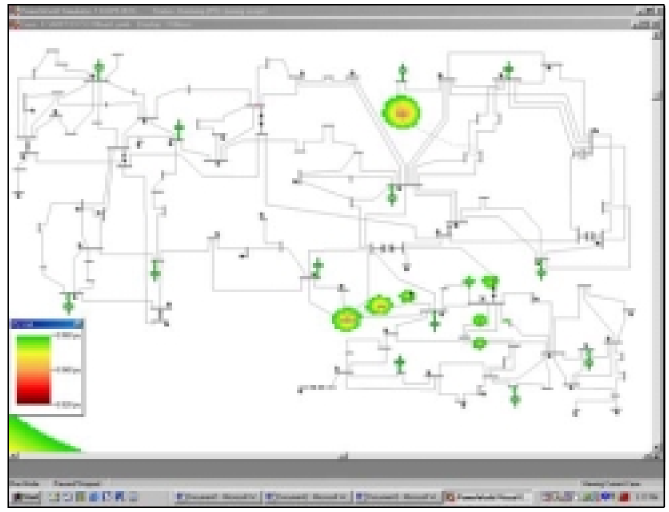

Figure 3: Contour-only One-line

Voltage violations were acknowledged by clicking directly on the symbol of the bus with the worst violation or on the darkest part of the contour. Once the worst violation was acknowledged the beeping would stop. Then, in a nearly identical procedure to the number-only group, the voltage violations were corrected by capacitor switching. The difference with this group was as the participate switched the capacitors the contour would be dynamically updated to indicate the new voltage values. Again, when all the voltage problems were fixed the scenario would automatically end.

3.3 Number-plus-contour

The one-line diagram with both numbers and color contours was a combination of the first two display conditions in that the voltages within limit were shown in small black numbers, and when the voltage violations occurred the voltages below limit would turn to large bolded red font surrounded by a white box, and at the same time the region surrounding the bus experiencing the low voltage became shaded using the same contour pattern used with the contour-only group. Acknowledging and solving voltage violations was identical to the procedure for the other two conditions. Figure 4 shows an example of this display condition.

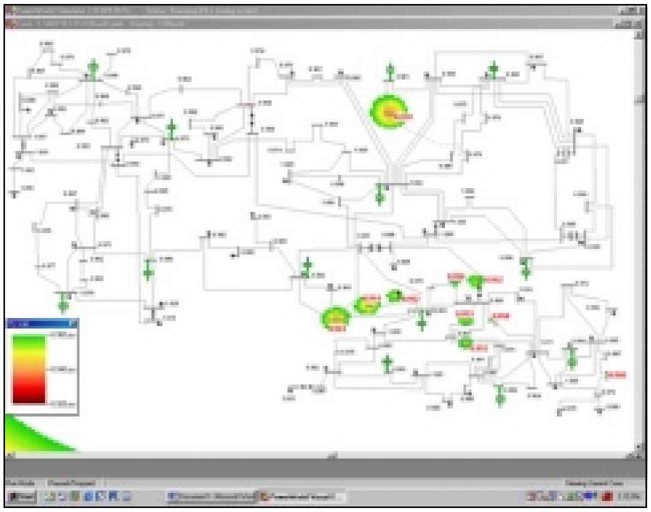

Figure 4: Number-plus-contour one-line

4. Procedure

Participants were randomly assigned to either the number-only condition (*n* = 15), or contour-only condition (*n* = 14), or the number-plus-contour condition (*n* = 14). Participants in each group were then provided with specific instructions about the display and tasks that they were to complete as part of the experiment. Participants were asked to read through the entire instructions and inform the experimenter when they were ready to proceed or ask questions if any came up.

Participants in each condition were presented with the power system information using the display format associated with their group assignment. Additionally, each of the participants across all conditions were administered the exact same four practice and twenty-six experimental trials. The order of the trials was the same for each group, with one or more low voltage violations occurring with each trial. Each trial began with the same base case condition, characterized by no voltage violations. Then, after a time delay of between 5 and 15 seconds a contingency occurred, which was signaled both by the computer beeping and one of the display conditions from Section 3. The same buses incurred voltage violations across the three display conditions during each trial, but the buses that incurred voltage violations changed from trial to trial. Participants were requested to be quick and accurate in acknowledging and solving the voltage violations. After all the voltage violations for a trial have been successfully corrected, a pop-up screen informed the participant of the successful solution. Participants then proceed to the next trial by clicking "OK". Testing was then terminated at the completion of all 26 trials.

5. Results and Discussion

Acknowledgement times were examined separately as a function of the complexity of the scenarios. There are certainly a number of different metrics that could have been used for assessing scenario complexity. Here the complexity of a scenario was measured by the number of voltage violations that occurred during that trial. In particular, the scenarios were divided into three groups according to their complexity, which were either low (the number of violations are less than 5), medium (the number of violations are between 5 and 8), or high (the number of violations are more than 8). The numbers of trials in each of these three complexity conditions are approximately equal (11, 7, and 8 trials, respectively).

Results of statistical analyses revealed that acknowledgement times across display groups did not differ on the low complexity tasks. However, as illustrated in Figure 5, acknowledgment times increased consistently across complexity conditions for the number-only group, yet increased only slightly for the number-plus-contour group and not at all for the contour-only group. Therefore, acknowledgement times did differ significantly ($p < .05$) across groups for both the medium and high complexity conditions. Specifically mean acknowledgement time for the contour-only group was significantly faster on both medium and complex tasks than that of the number-only group and the number-plus-contour group. Although the mean acknowledgment time for the number-plus-contour group was also generally quicker than that of the number-only group, this difference was significant ($p < .05$) for the high complexity trials only.

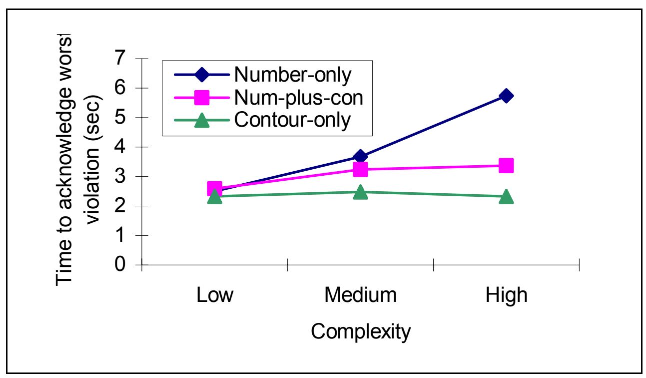

Figure 5: Acknowledgement Times As a Function of Scenario Complexity

The number of acknowledgements that participants made per trial was used as a measure of accuracy, with fewer acknowledgments reflecting a greater level of accuracy. As can be seen in Figure 6, acknowledgements within the contour-only, and number-plus-contour groups differed only slightly across different complexity levels, but the number of acknowledgements for the number-only group increased consistently as the complexity of the scenarios increased. Statistical analyses revealed that for the high complexity condition, the number of acknowledgements for the number-only group was significantly higher ($p < .05$) than those of the contour-only group and the number-plus-contour group, whereas the number of acknowledgments for the number-plus-contour group was not significantly different form that of the contour-only group.

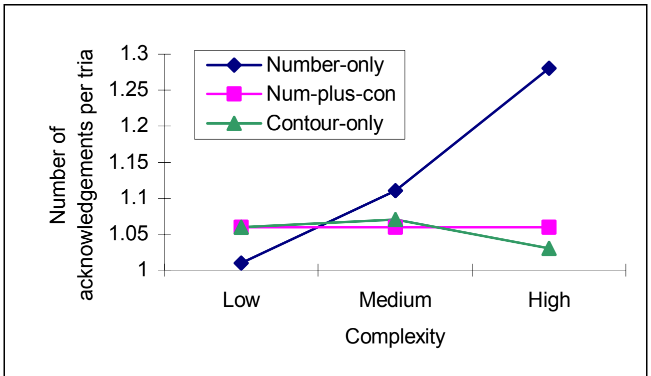

Figure 6: Acknowledgement Accuracy As a Function of Scenario Complexity

Solution times were also examined as a function of scenario complexity. The results of these analyses revealed solution times for the number-only group was significantly faster ($p < .05$) than that of the number-plus-contour group, and the contour-only group. However, solution times were not significantly different between the contour-only and the number-plus-contour groups. As can be seen in Figure 7, except for the number-plus-contour group, solution times increased as the scenarios became more complex.

This finding was surprising given that the exact numeric value of the voltage violation was not needed to remedy the problem. Therefore, one of the possibilities for these findings was that the contours created display clutter that hindered solution times by covering up the capacitors necessary to solve the violations. Therefore, to examine this issue, scenarios were parsed according to whether the contours covered capacitors ($n = 6$) or did not cover any capacitors ($n = 20$). As expected, differences in solution times between groups was much less on trials in which the capacitors were uncovered than on trials in which the capacitor needed to solve the problem was covered by the contour (see Figure 8).

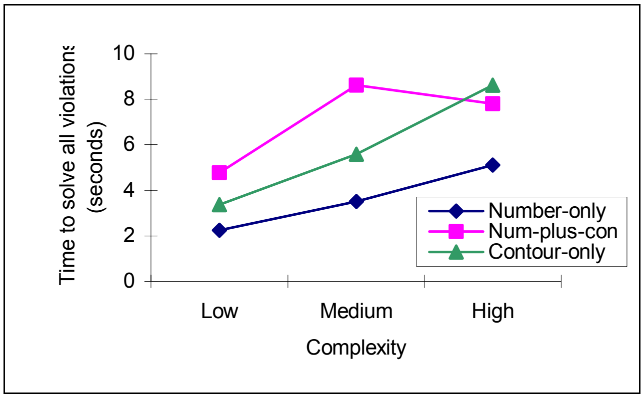

Figure 7: Solution Time As a Function of Scenario Complexity

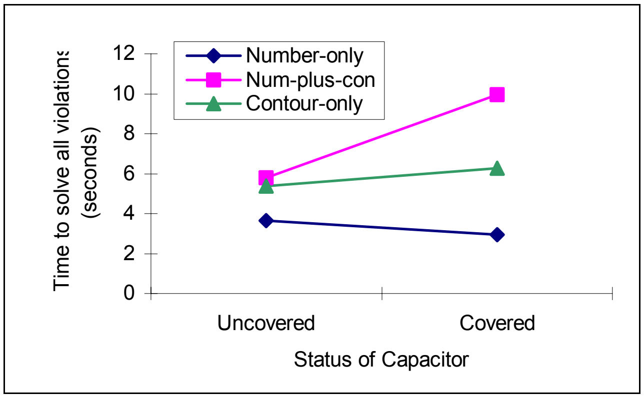

Figure 8: Solution Time As a Function of Capacitor Coverage

The number of capacitors used per trial to solve the voltage violations was examined as a measure of performance efficiency, with fewer capacitors closed reflecting more judicial use of system components. Similar to solution times, the mean number of capacitors used per trial for the number-only group was significantly lower than that of the number-plus-contour group and the contour-only group. But the number-plus-contour group did not significantly differ from the contour-only group (See Figure 9).

Solution accuracy was also analyzed as a function of the capacitor status (covered vs. uncovered) to explore issues of contour clutter. As expected, the numbers of capacitors used to solve did not significantly differ from one another for the uncovered trials, but did differ significantly across groups for covered trials. For the covered trials, however, the number of capacitors used to solve for the number-only group was significantly less than that of the number-plus-contour group and the contour-only group. But the number-plus-contour group did not significantly differ from the contour-only group.

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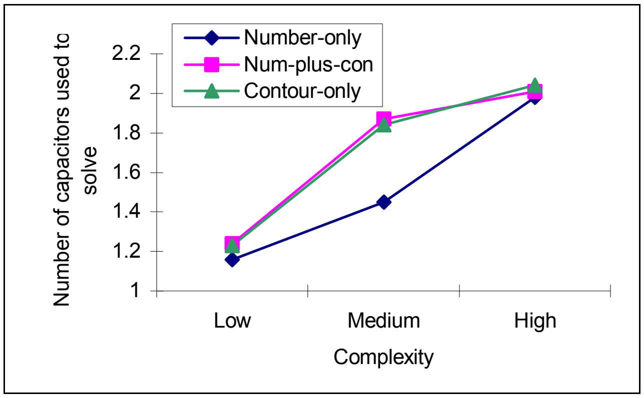

Figure 9: Solution Efficiency versus Scenario Complexity

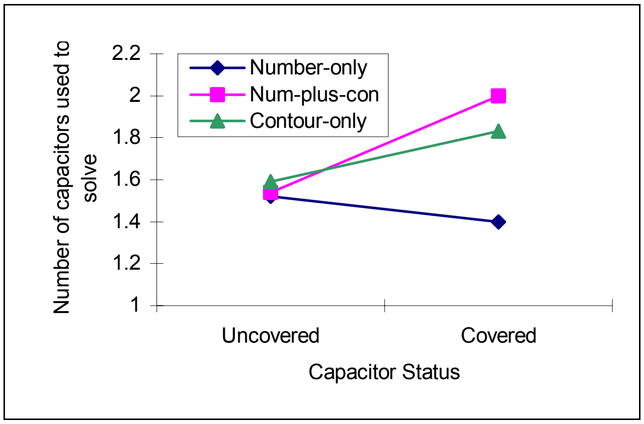

Figure 10: Solution Efficiency As a Function of Capacitor Coverage

6. Conclusion

Color contouring was expected to attract users' attention to the worst voltage violations, thereby facilitating both acknowledgment speed and accuracy compared to a numeric display. This hypothesis was generally confirmed, particularly when a large number of violations simultaneously existed within the power grid. However, the benefits of contouring also came with a cost. In particular, contouring generally slowed the speed and accuracy by which users could solve or remove the voltage violations within the system compared to the numeric display. An in-depth analysis revealed the nature of this cost was due to the increased display clutter associated with the contouring. In particular, the contours were covering up the relevant capacitors thereby delaying their selection. Remedying this cost/benefit trade-off between contours and numbers does not appear to be as simple as combing the two display features. Indeed, under certain conditions the combination of these features in the display was found to produce worse performance than either display feature individually. Apparently, users are not able to ignore one dimension (e.g., numbers) while using the other (e.g., contours). An alternative option may be to incorporate dimming features that can be used to make the relevant color or numeric code more salient, or a toggling feature that allows users to switch each feature on or off depending on the particular task. Still, whichever features are chosen, the present study underscores the need for formal usability and human factors research to test the effectiveness of specific visualization techniques.

7. Acknowledgement

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